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Lessons learned from using expert elicitation to identify, assess and rank the potential leakage scenarios at the Heletz pilot CO_2 injection site.

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Abstract

Expert elicitation is a useful approach to synthesis expert knowledge, experience and insight when the input data and analysis is limited. During the early stages of the EU FP7 MUSTANG pilot CO_2 injection experiment at Heletz, Israel there was very little input data available, yet decisions had to be made regarding data collection, drilling, operation and monitoring strategies. An expert elicitation study was undertaken to identify, assess and rank potential CO_2 leakage scenarios at Heletz to provide guidance to support the decision making processes. This paper presents a critique of the expert elicitation process undertaken, presenting the methodology and a discussion of the results. We present the lessons learned during the expert elicitation process, highlighting its advantages and limitations and provide suggestions on ways to overcome these limitations. Our findings show that prudent expert elicitation can make a valuable contribution to decision making, however if done improperly it can equally lead to invalid or misleading results and wrong decisions.

Keywords:

Heletz CO_2 storage;

Caprock integrity;

Expert elicitation

Lessons learned during elicitation

Caprock leakage scenarios

1. Introduction

The capture and storage of CO_2 (CCS) in depleted hydrocarbon reservoirs and deep saline formations has been proposed to reduce anthropogenic CO_2 emissions, mitigating global climate change (IPCC, 2006; Bachu and Adams, 2003 and Benson and Cole, 2008). Stored CO_2 is physically trapped by low permeability caprocks, therefore understanding the long term integrity of the caprock seals is a pre-requisite for CO_2 storage security, Bachu (2003), Li et al. (2005 & 2006), Class (2009), Bildstein et al. (2009), Ketzer et al. (2009), Fischer et al. (2010), Wollenweber et al. (2010), Gaus (2010) IEAGHG 2011 and Amann et al. (2011).

The Heletz field is the pilot CO_2 injection experiment for the EU FP7 MUSTANG project (Niemi et al. 2012 & 2015). Heletz is an abandoned oil field with partial legacy reservoir data, and as such during the initial stages of the Heletz site assessment there was a high degree of uncertainty associated with potential leakage scenarios (IAEGHG, 2009). Expert elicitation is a “systematic approach to synthesise the reasoned and subjective judgments of experts where there is uncertainty due to insufficient data, making explicit the inherent knowledge based on experience and expertise” (Slottje et al. 2008). It can be used as a structured approach to systematically consult experts on uncertain issues (Barke et al. 1993) and most often used to quantify ranges for poorly known parameters. With this in mind expert elicitation was chosen as a method to explore the leakage uncertainties at Heletz with the aim of producing a quantifiable input to supplement the limited field data, site characterisation and numerical simulation data. The elicitation was designed to identify, assess and rank the potential leakage scenarios to support the assessment and decision making for early data collection, field operation and monitoring strategies.

Expert elicitation has been widely used in uncertainty analysis, (Hora, 2009; Cooke, 1991, Knol et al. 2010 and Mosleh et al. 1988) where expert knowledge, experience and insight are crucial if the input data and analysis is poorly understood, complex and there is limited 'hard' input data, (Meyer and Booker, 2001). It has been successfully used within in the fields of nuclear waste, climate change and environmental assessment; each areas where there is a lack of established datasets and field experience and as such requires the collation of skills and experience from a wide range of disciplines to form a coherent judgement, (Kotra et al. 1996, Risbey et al. 2000, Wardekker et al 2008 and Van Gijlswijk et al. 2004).

For the purpose of this study, a scenario is defined as the source of potential CO_2 leakage through the caprock including external leakage processes such as those in the wellbore and includes:

- Direct leakage pathway routes such as matrix permeability, geological heterogeneity, fractures and wells;
- Dispersion routes such as capillary forces, diffusion, wettability etc.;
- Leakage sources such as injection pressures and well position;
- Mineral reactivity pathways such as mineral dissolution, precipitation, clay swelling, etc.;
- Fluid properties influencing leakage such as density, viscosity, relative permeability etc. and
- Any additional factors that may impact on storage security such as thermal conductivity or the compressive strength of the caprock.

In addition to an overview of the Heletz site and the generation of the inventory of leakage scenarios at Heletz, this paper provides an overview of expert elicitation, followed by a critique of the expert elicitation methodology used in this study. The results are presented and discussed along with a comparison with findings from conventional risk assessment studies undertaken at other CO_2 injection and storage pilot projects in Otway, Australia; Weyburn, Canada and In-Salah, Algeria. The paper discusses and critically reflects on some of the lessons learned during the expert elicitation, its limitations and suggests ways to overcome them. Prudent expert elicitation can make a valuable contribution to decision making, however if done inappropriately it can equally lead to invalid or misleading results, wrong decisions and contribute to discrediting the practise of expert elicitation.

2. Heletz site geological overview

The Heletz site is located on the Southern Mediterranean Coastal Plain of Israel and is a part of an oil field discovered in 1955. The Heletz structure is an anticline fold, gently dipping to the east, truncated by a pinch-out line to the west with a crest of about 2 km by 4 km and a vertical closure of 70 m, (Shtivelman at al. 2010), Figure 1. The Heletz formation was deposited during thermal subsidence at a passive margin (Steinberg at al., 2008) and the Heletz reservoir consists of three Lower Cretaceous sand layers; 'K', 'W' and 'A' separated by shales of various thicknesses deposited within sequences of repeated regressive – transgressive depositional sequences, (Eppelbaum and Katz, 2011). Offshore sand and clay, shoreface silts, tidal flats and lagoonal shales deposits are all suitable as caprocks. The Heletz 'K' sands are interpreted as offshore marine and the Heletz 'A' and 'W' sands are interpreted as tidal channel and or lagoonal sands (Amireh, 1996). The reservoir sands have a maximum thickness of 21m in the south-east, with the lateral extension of the sand layers limited to the west by the pinch-out where the sands are replaced by shales. The caprock overlaying the reservoir is represented by a shale and marl unit with a thickness increasing from 23 m in the north to 54 m in the south. Full details of the Heletz site can be found in Niemi et al. (2015), which also presents the most up to date field data, none of which was available to the MUSTANG consortium members at the beginning of the project. It was this lack of data from which to make the data collection, field operation and monitoring strategy decisions was the primary reason the expert elicitation was undertaken.

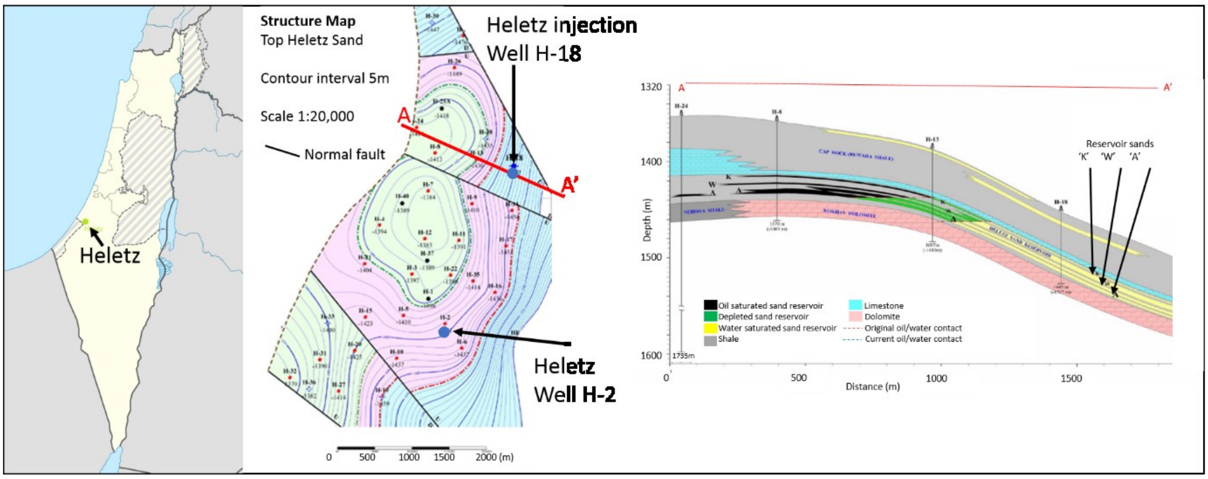

Figure 1 Heletz location map, structure map and reservoir cross section

3. Heletz caprock leakage scenario inventory (screening of the uncertainties)

The generation of a comprehensive inventory of leakage scenarios is the first step towards undertaking the effective expert elicitation required to assess and rank the potential leakage scenarios at the Heletz pilot CO_2 injection site. In order to identify all of the potential CO_2 leakage scenarios, a thorough and systematic search through published peer reviewed literature using relevant keywords, theories / concepts, prominent authors and paper reference lists was conducted until no new papers or sources were identified. Six primary influences controlling potential caprock leakage were identified:

- **The caprock matrix properties**; which focusses on how the inherent properties of the matrix rocks could influence the sealing ability of the caprock and includes the caprock matrix pore throat size, pore compressibility, mechanical properties, porosity, permeability, anisotropy and thermal conductivity.
- **Mineralogy**; which focusses on how the inherent mineralogy and its potential reactivity with migrating CO_2 rich fluids could influence the sealing ability of the caprock and includes precipitation and dissolution reactivity, clay mineral shrinkage / swelling and changing pH.
- **The injection, formation and migrating fluids**; which focusses on how fluid properties would be influenced by any change in pressure, temperature and exposure to migrating CO_2 and how these fluids would interact with the caprock matrix and pore space and includes fluid pressure, density, viscosity, temperature and solubility along with relative permeability and free phase CO_2. It also includes wettability, interfacial tension, sorption, and electrostatic forces.
- **The stress state, fracture network and fracturing potential**; which focusses on how the stress state, existing fracture network and consequences of changing pressures and stress could influence the integrity of the caprock and includes field stress state, injection pressures, hydraulic fracturing, thermal fracturing and fracture opening threshold along with existing fracture density, geometry and distribution, fracture permeability / sealing fracture aperture and induced microseismicity.
- **The geological architecture;** which focusses on how the geology could influence the sealing ability of the caprock and includes high permeability conduits in the caprock, lithological discontinuities, caprock or reservoir rocks dipping to surface and reservoir rock unconsolidation.
- **The wellbore environment**: which focusses on how the legacy, drilling, well completion and injection could influence the sealing ability of the caprock and focusses on improperly abandoned wells, poor sealing of the injection well, injection rate and position, impurities within the injection stream, geothermal gradient and joule Thomson cooling generating

geothermal stresses and the consequence of any additional monitoring equipment / techniques.

These scenarios are the uncertainty criteria assessed during the expert elicitation. All scenarios identified were included, even those which may seem immaterial, such as Joule-Thomson cooling, because any potential leakage scenario not identified and included at this early stage would be completely excluded from further analysis and assessment. The inventory was circulated within the EU FP7 MUSTANG research project group, to ensure that within the academic expertise of the MUSTANG project all possible leakage scenarios through the caprock had been identified. The scenarios were also referenced against the CO_2 FEP Quintessa database (2014) to ensure all potential leakage scenarios had been captured. Forty four potential CO_2 leakage scenarios influencing the Heletz caprock integrity were identified, Figure 2. These leakage scenarios became the basis of the expert elicitation exercise and a brief synopsis of each leakage scenario identified including the limited Heletz data that was available at the time of the elicitation was given to each expert prior to elicitation. This information can be seen in the supplementary information at the end of the paper.

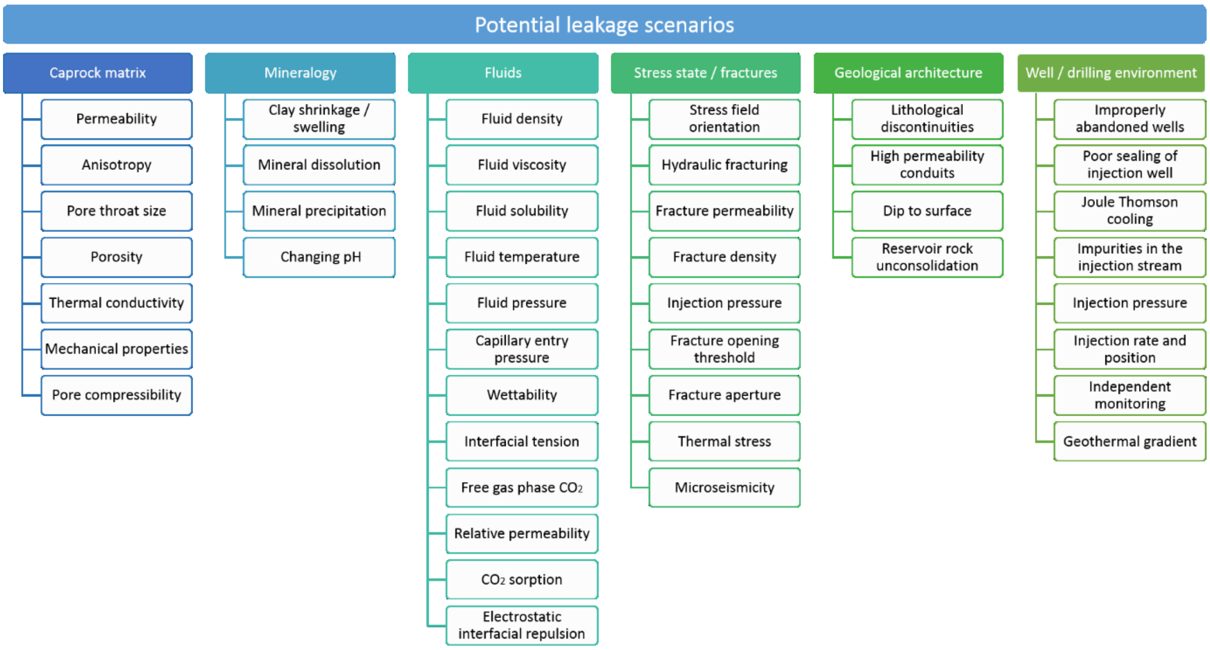

Figure 2 The Heletz caprock leakage scenario inventory

4. Expert Elicitation

Expert elicitation stems from probabilistic risk assessment (PRA) which relies on exert judgement when data is sparse or non-existent (Kuhnert at al. 2010), as was the case at the early stages of the Heletz site characterisation. Experts are qualified individuals who have knowledge on the subject through their practise, training and experience, identified on the basis of their qualifications, experience, professional membership and peer recognition (Booker and McNamara 2004, Ayyub 2001). However expert judgement has inherent uncertainty, with experts subject to biases within their personal context, assumptions, beliefs and experience (Anderson and Hattis 1999; Shrader-Frechette 1996; Camerer and Johnson 1997). Expert judgement can also be influenced by the processes used to elicit it. The elicitation methodology must account for these uncertainties within expert opinions to extract the knowledge in as raw and unbiased way as possible using a systematic well designed elicitation approach. Expert elicitation is not a low cost replacement to data collection and analysis, but when a decision needs to be made quickly or within a limited budget a well conducted expert elicitation can provide valuable insight and guidance to decision makers. Figure 3 presents an outline of the expert elicitation undertaken for the Heletz site which was designed to identify, assess and rank the potential leakage scenarios to support the assessment and decision making for early data collection, field operation and monitoring strategies.

Figure 3 Expert elicitation procedure

4.1. "Expert" selection

Is anyone really an expert? No-one will be an expert in all aspects of the problem, so the objective of the expert selection was to achieve a well-balanced sample of experts who are able to make judgements on the range of uncertainties that are to be elicited. Three different types of experts are desirable (Kotra et al., 1996, and Loveridge, 2002) to assess the potential CO_2 leakage scenarios; the generalist who has substantive knowledge in one relevant subject area and a good understanding of the technical aspects of the whole CO_2 storage system; the subject-matter experts who are recognised by the peers as authorities in their relevant subject area and finally the normative experts who are experience in probability theory and decision analysis to assist the generalist and subject-matter experts.

The European Community's Seventh framework Programme MUSTANG collaborative project into the quantification of deep saline formations for CO_2 storage, comprises 19 international institutions (Universities, Research Institutes and SME's) that included a judicious balancing of the major disciplines required to undertake field characterisation, processes, modelling and assessment. These 19 institutions formed the pool from which the "experts" were approached directly.

For this study, 12 "experts" from 9 different international institutions of different expert types undertook the expert elicitation. The "experts" were all from the MUSTANG consortium so we cannot claim to have captured all the CCS experts, however according to a panel of expert elicitation practitioners, (Cooke and Probst, 2006) at least six experts should be included; otherwise there may be questions about the robustness of the results, however beyond 12 experts, the benefit of including additional experts begins to drop off. It is also possible that these experts could be viewed as pro-CO_2 storage, however these biases can be minimised with a well-designed elicitation procedure.

4.2. Uncertainties to be addressed by expert elicitation

Uncertainty assessments ideally use a quantitative assessment, however when comparing risks of different natures or with limited sensitivity analysis, a common quantitative unit is very difficult to determine, (Sjoberg et al., 1993). Quantitative assessment is also difficult within the CO_2 storage system due to a wide range of primary controlling parameters (DNV 2003), technological uncertainty and the fact this study was based on early incomplete Heletz site data. Therefore a qualitative assessment was required to assess the leakage scenarios. Without quantitative assessment criteria, caution should be exercised when using qualitative words such as "unlikely" or "possible" to describe the scenario uncertainty. Critical difference between the views of different experts can be missed (Wallsten et al. 1986 and Wardekker et al 2008), as the same word can mean different things to different people. To avoid this confusion within the Heletz assessment criteria the following semi-quantitative scenario uncertainty assessment criteria were used:

- Severity of effect of leakage; i.e. how extensive would the CO_2 leakage be? Could that particular scenario at worst lead to leakage into the first few mm's of the caprock, or could it lead to CO_2 intrusion above the top caprock?
- Immediacy of occurrence; i.e. the time period of the leakage. Would it be more likely that that any leakage of CO_2 influenced by a particular scenario would occur during injection or was it more likely to occur over many thousands of years?

Psychometric literature indicates a diminishing return after ~eleven scale points within question answer options, (Nunnally and Bernstein, 1994). Studies have also shown that respondents have difficulty defining their point of view on a scale greater than seven, therefore if more than seven response choices are provided, respondents are likely to start picking answers randomly, which can make the data irrelevant, (Nunnally and Bernstein, 1994). It is also useful to use a scale with odd numbers, so there is a midpoint as a reference point. Therefore for the Heletz study a five-point scale for severity and immediacy was used, Table 1 where the scenario uncertainty criteria scales comply with the "transversality" principle, in that the lowest value relates to the lowest impact of leakage, and vice versa for the highest value.

Table 1 Scenario uncertainty scales

Severity value	Expert elicitation scenario uncertainty criteria	Immediacy value	Expert elicitation scenario uncertainty criteria
1	CO_2 intrusion into the first few mm of the primary caprock	1	Leakage happens after 10000 years
2	CO_2 intrusion above primary caprock layer	2	Leakage happens after 1000 years
3	CO_2 intrusion above secondary caprock layers	3	Leakage happens after 100 years
4	CO_2 intrusion above tertiary caprock layer	4	Leakage happens after 10 years
5	CO_2 intrusion into top overburden / to surface	5	Leakage happens during the injection period

4.3. Pre-elicitation "expert" training

The "experts" were provided with a briefing document prior to the elicitation. This contained a copy of the elicitation question and unbalanced key information providing a brief synopsis of each leakage scenario identified, including the limited Heletz data that was available at the time of the elicitation, to encourage the "experts" to start thinking about their response in advance. The information provided to the "experts" can be seen in the supplementary information at the end of the paper. The information also highlights the lack of relevant site specific data for Heletz and reinforces the importance of the expert elicitation exercise as a tool to aid the early assessment and decision making for data collection, field operation and monitoring strategies.

4.4. Expert elicitation methodology

A thorough preparation, systematic design and prudent implementation of an expert elicitation process may increase the validity of its outcomes and the transparency and trustworthiness of its conclusions, (Clemen and Winkler, 1999). There are three elicitation process options; (1) personal interviews, (2) group elicitation sessions and (3) individual questionnaires. Resource wise personal interviews were not possible under the scope of this study. Group elicitations have a number of benefits that include sharing of knowledge and better appreciation of different disciplinary viewpoints, (Clemen and Winkler, 1999). However group interaction can be influenced by dominant personalities in the group and the implicit suggestion of the "need to achieve consensus", (Loveridge, 2002). Therefore individual questionnaires were chosen as the Heletz elicitation method to reduce bias by suggestion, ensuring answers were not based on a consensus, but rather an individual opinion. The questionnaires were anonymous to minimise the possibility of "experts" feeling exposed by their answers.

For this study the elicitation question was "What is your best guess of the likely severity (extent of the leakage) and immediacy (time frame) potential of CO_2 leakage for each identified leakage scenario?" of which there are 44. It is important to note that considerable time and care along with multiple iterations of format and question wording was undertaken and tested on colleagues before the final format, question and scale was decided upon.

The MUSTANG consortium held meetings every six months, so the questionnaire was completed during a workshop timetabled during a consortium meeting, with a one hour timeslot, to ensure the best availability of "experts" both in terms of time and engagement. During the elicitation workshop an introduction was given which covered:

- An explanation of the elicitation procedure and subject.
- It is important that the pre-elicitation training makes the "experts" aware of potential unconscious bias and guides the "experts" towards expressing their judgements in probabilistic terms, raising awareness of the unconscious bias in human judgement.
- Experts often select a first anchor point as a first approximation of the assessed scenario and adjust this to the required assessment as the supplementary information is considered (Morgan and Henrion 1990). Reminding the participants to think of the reasoning to support their judgments and consider how the results could be different during the questionnaire answering process may help to improve the quality of their assessments.
- Explain consensus is not the primary objective, differing views reveal valuable information about the scenario uncertainty.

When eliciting expert opinion, the results must be treated with caution as individuals, including experts, are subject to defined cognitive biases which will affect their judgement in situations of uncertainty (Kahneman et al., 1982). These biases which include over-confidence, expert level and motivational bias are the result of decision making processes based on personal experience and personality that are used to simplify the often multifaceted complex scenarios. For each leakage scenario assessed a personal expert level was also requested to identify whether expert level had an impact on judgment, Table 2.

Table 2 Expert level descriptors

Level of expertise	
1	Novice - no knowledge at all of the leakage scenario.
2	Limited knowledge - some awareness and knowledge of the leakage scenario
3	Competent - working knowledge of the leakage scenario
4	Knowledgeable - research activity and peer reviewed publications of the leakage scenario
5	Expert - recognised expert through research, peer reviewed papers and keynote speaker in this leakage scenario

Each participant was provided with a blank questionnaire and the supplementary information and asked to assign their best guess severity, immediacy and "expert" level for each leakage scenario in turn. The questions were asked one at a time and the "experts" filled in the questionnaire and all participants moved onto the next scenario, being reminded at all times of the points above and time given for discussion if required. Working through the questionnaire as a group of individuals one question at a time would minimise the chances of the "experts" getting bored or providing lax or random middle ground answers to maximise the potential for a serious and considered response and increase the validity of the results. The elicitation process also required a good deal of encouragement requiring frequent persuasion and reassurance, particularly with regard to classifications, terminology and most importantly the lack of field data, which was the reason behind the elicitation process in the first instance. It was a challenge to change a mindset when an "expert" is experienced in working with actual field data in a more numerical and less interpretive discipline, constant reference was required to get the "experts" to make a judgement on each leakage scenario based on the semi-quantitative scenario uncertainty assessment criteria in table 1.

4.5. Data analysis

The expert elicitation generated a best guess severity and a best guess immediacy. This provided a database of 12 completed questionnaires from which to collate and analyse the data. Mathematical methods were implemented to combine the "expert's" answers which focused on the simple summary methods of arithmetic average giving equal weight to all experts. Work by Clemen and Winkler, (1999) concludes that a simple average is often the best performing aggregation method, as it is less sensitive to the input assumptions than some of the more powerful Bayesian aggregation techniques such as that suggested in Morris (1977). It is important to note that heterogeneity and diversity amongst expert views provides valuable insight and to a certain degree this can be captured by the standard deviation within the arithmetic averages.

These simple mathematical aggregation methods however do not allow for the consideration of factors such as over confidence amongst experts (Clemen and Winkler, 1999) and more robust statistical methods have been suggested by Cooke and Goosens (2008) which include seed questions to provide calibration scores.

To rank the leakage scenarios the average expert's data for severity and immediacy were plotted in a probability and impact matrix. This assigns an impact rating from low, medium low, medium, high to very high (Figure 4) for the leakage scenarios based on combining the severity and immediacy values. Any leakage scenarios that plot within the very high severity and immediacy category on the matrix will require further analysis, an increased data collection and sensitivity analysis effort and enhanced monitoring and mitigation strategies.

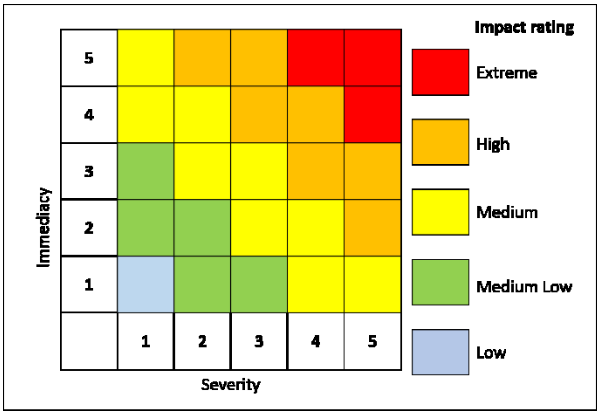

Figure 4 Probability and impact matrix scales (impact rating)

5. Results

The probability and impact matrix results were grouped per primary category, and can be seen in Figures 5 to 10. The impact rating of each scenario within the probability and impact matrix facilitated the ranking of the leakage scenarios, based on whether the scenario plotted in the most extreme to the lowest impact rating category on the probability and impact matrix.

The results of the ranking of the leakage scenarios based on impact rating can be seen in Table 3. The ranked leakage scenarios reveal the leakage scenarios that pose the highest likelihood of CO_2 leakage and as such merit the highest effort of data collection and sensitivity analysis effort and enhanced monitoring and mitigation strategies.

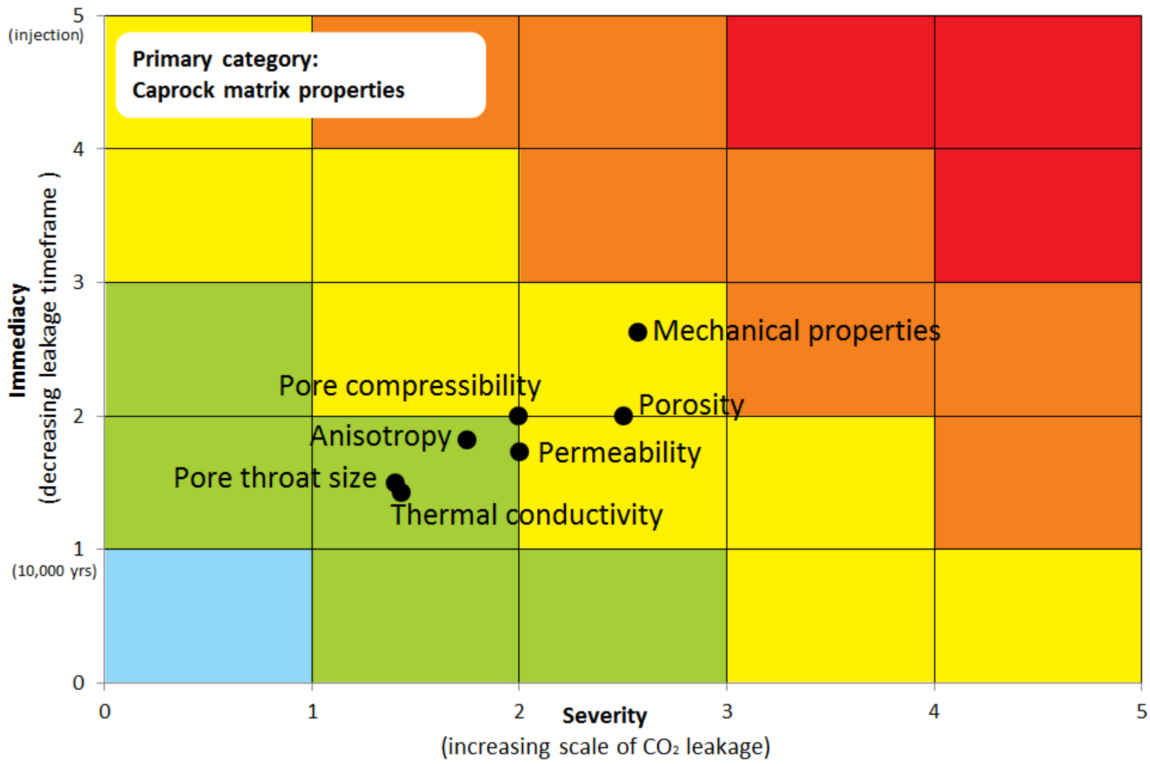

Figure 5 Probability and impact matrix for the caprock matrix properties

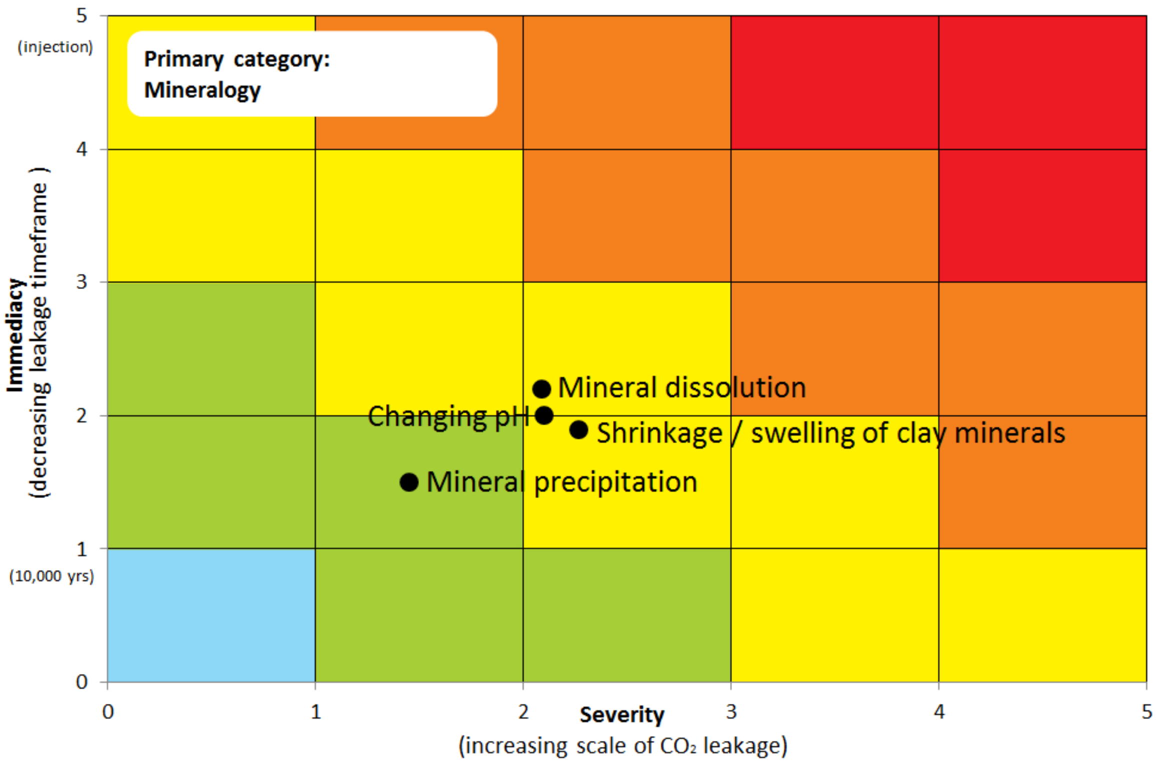

Figure 6 Probability and impact matrix for the mineralogy

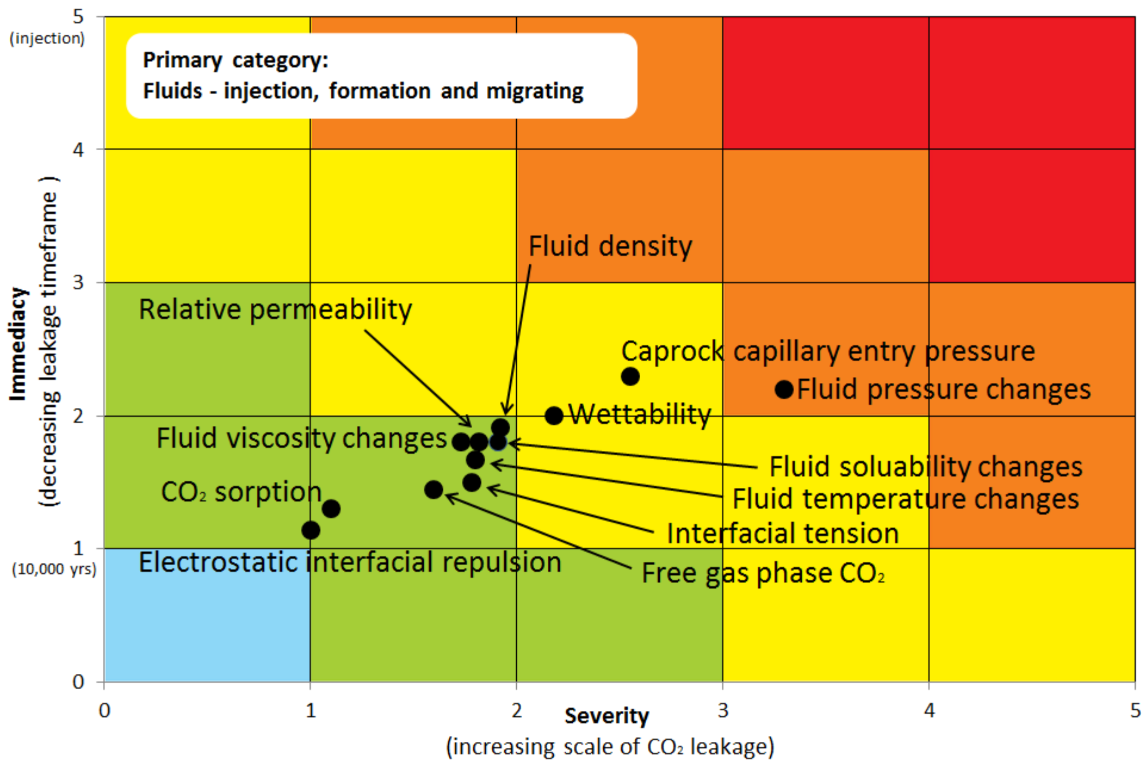

Figure 7 Probability and impact matrix for the caprock / reservoir injection, formation and migrating fluids

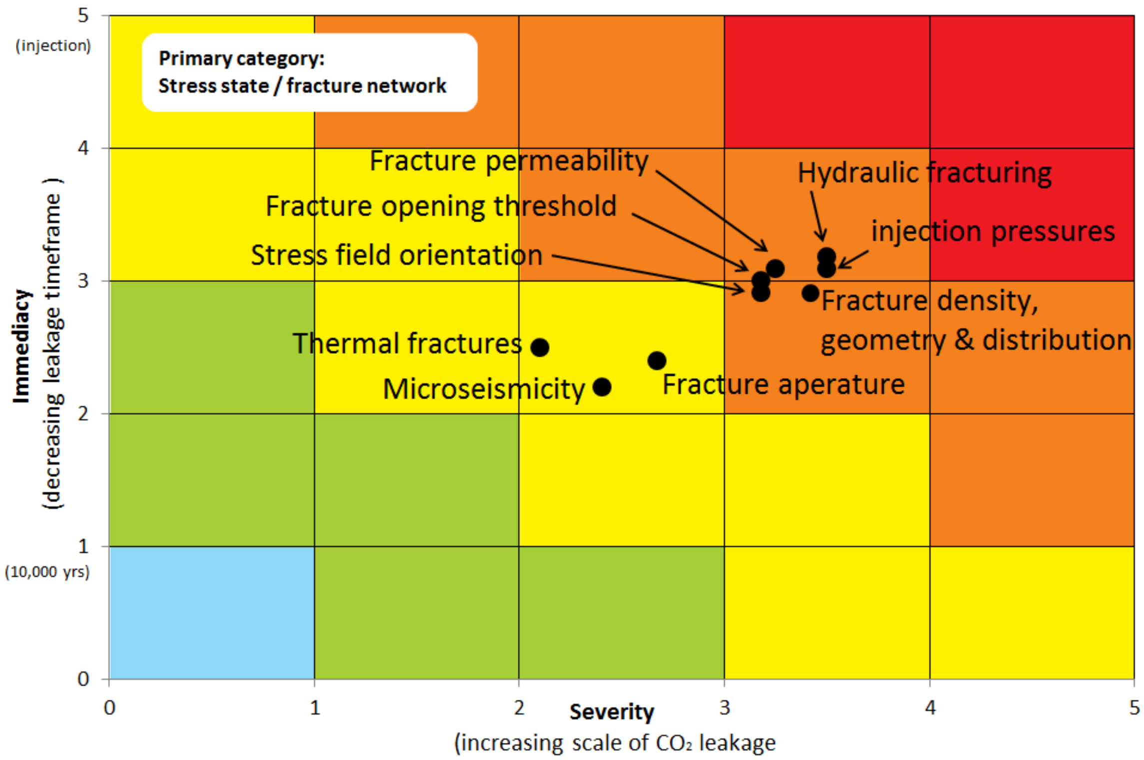

Figure 8 Probability and impact matrix for the caprock stress / fracture network / fracturing potential

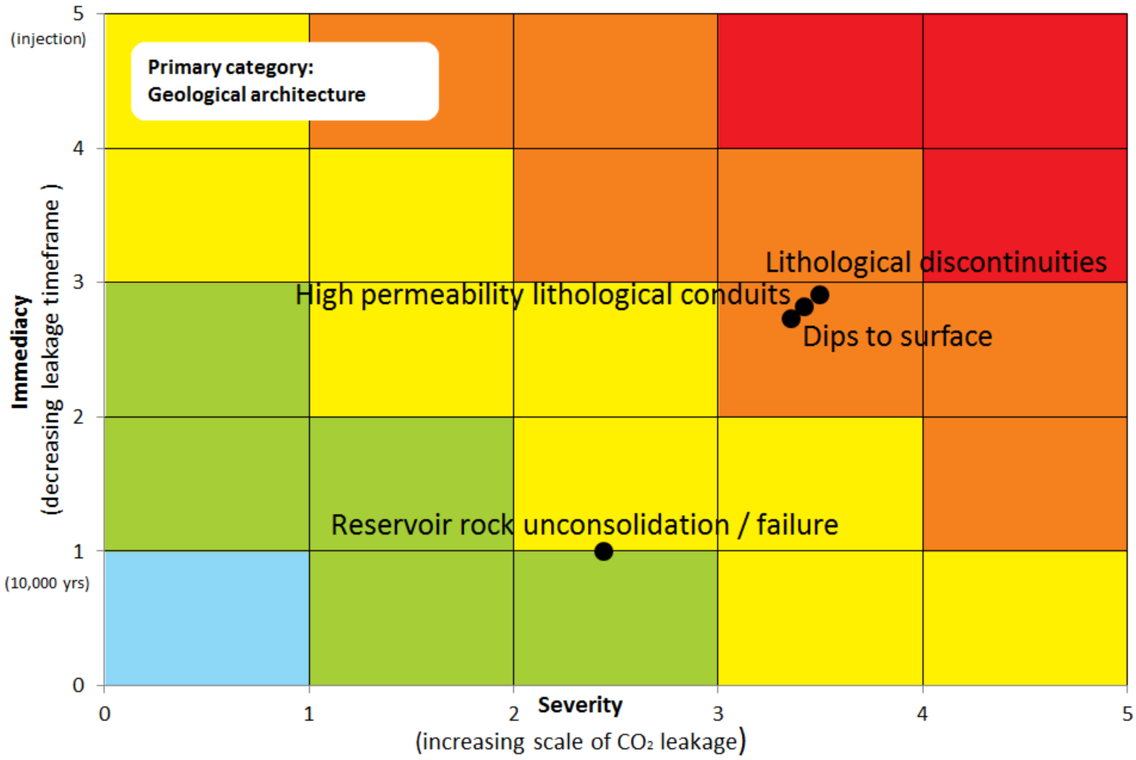

Figure 9 Probability and impact matrix for the geological architecture

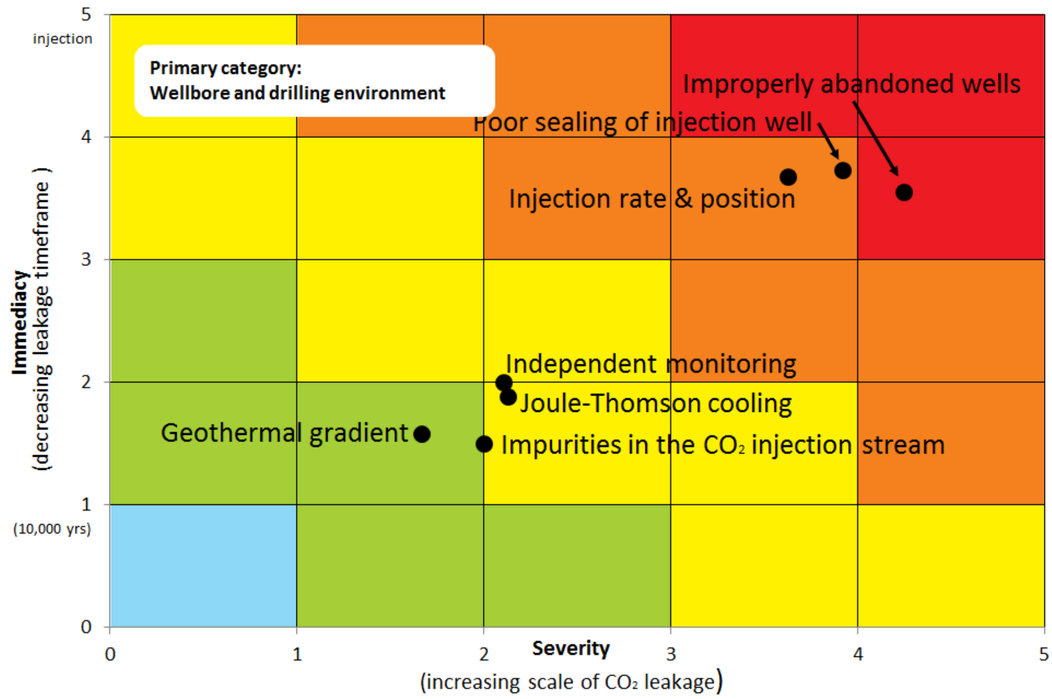

Figure 10 Probability and impact matrix for the wellbore and drilling environment

Table 3 Results of the probability and impact matrix in ranked order.

Impact Rating	Impact Ranking	Leakage scenario
Extreme impact rating scenarios	1	Improperly abandoned wells
High impact rating leakage scenarios	2	Poor sealing of the injection well
	3	Injection rate / position (if *injection rate above poorly defined capillary entry pressure or caprock tensile / compressive strength*)
	4	Hydraulic fracturing (*if fracture propagation values are lower than expected*)
	5	Injection pressures (if *above capillary entry pressures or fracture propagation*)
	6	Fracture permeability (*if an unexpectedly high fracture permeability*)
	7	Caprock mechanical properties (*if lower than expected*)
	8	Fracture opening thresholds (*if lower than expected*)
	9	Lithological discontinuities in the caprock (*if caprock less continuous*)
	10	Fracture density, geometry and distribution (*if unexpectedly high fracture density*)
	11	High permeability lithological conduits in the caprock
	12	Stress field orientation (*if improperly evaluated*)
	13	Caprock and storage reservoir dipping to surface (*if reservoir has a surface outcrop*)
	14	Fluid pressure changes (*if increase to cause fracturing / movement*)
Medium impact rating leakage scenarios	15	Fracture aperture (*if larger than expected*)
	16	Caprock matrix compressive strength (*if lower than expected*)
	17	Reservoir rock unconsolidation / collapse
	18	Caprock capillary entry pressure (*if lower than expected*)
	19	Thermal fracturing (*occurring*)
	20	Micro seismicity (*occurring*)
	21	Matrix total porosity (*if higher than expected*)
	22	Mineral dissolution (*if higher than expected*)
	23	Wettability (*if lower than expected*)
	24	Independent monitoring (*does it increase confidence or data quality*)
	25	Reducing pH (*of formation fluids*)
	26	Clay mineral shrinkage (*CO_2 dehydration or occurring in the presence of CO_2*)
	27	Joule Thomson cooling (*during any depressurisation*)
	28	Pore compressibility (*if wrongly characterised*)
	29	Matrix permeability (*if wrongly characterised*)
	30	Impurities in the CO_2 stream (*if above the percentage tolerance*)
Medium-Low impact rating leakage scenarios	31	Fluid density changes
	32	Fluid solubility changes (*if wrongly characterised*)
	33	Caprock relative permeability to CO_2 (*if wrongly characterised*)
	34	Matrix anisotropy (*if wrongly characterised*)
	35	Fluid viscosity changes (*if wrongly characterised*)
	36	Fluid temperature change
	37	Interfacial tension (*if lower than expected*)
	38	Geothermal gradient (*if significantly different to expected*)
	39	Free phase gas CO_2 (*present*)
	40	Mineral precipitation (*if wrongly characterised*)
	41	Pore / pore throat size (*if wrongly characterised*)
	42	Thermal conductivity (*if wrongly characterised*)
	43	CO_2 sorption (*does not occur*)
	44	Electrostatic interfacial repulsion (*if poorly defined clays*)
Low impact rating leakage scenarios	-	None

The results show that there was one extreme impact rating leakage scenario identified by the "experts", that of improperly abandoned wells and thirteen high impact leakage scenarios that the "experts" believe pose the highest likelihood of CO_2 leakage. These fourteen leakage scenarios merit the highest effort of data collection, sensitivity analysis effort and enhanced monitoring and mitigation strategies:

- Improperly abandoned wells
- Poor sealing of the injection well
- Injection rate / position (if injection rate above poorly defined capillary entry pressure or caprock tensile / compressive strength)
- Hydraulic fracturing (if fracture propagation values are lower than expected)
- Injection pressures (if above capillary entry pressures or fracture propagation)
- Fracture permeability (if an unexpectedly high fracture permeability)
- Caprock mechanical properties (if lower than expected)
- Fracture opening thresholds (if lower than expected)
- Lithological discontinuities in the caprock (if caprock less continuous)
- Fracture density, geometry and distribution (if unexpectedly high fracture density)
- High permeability lithological conduits in the caprock
- Stress field orientation (if improperly evaluated)
- Caprock and storage reservoir dipping to surface (if reservoir has a surface outcrop)
- Fluid pressure changes (if increase to cause fracturing / movement)

There are also sixteen medium impact rated scenarios, fourteen medium low rated impact scenarios and no low impact rated scenarios.

6. Discussion of the elicitation results

When looking at the leakage scenario results in detail there are a number of interesting or what might be considered conflicting findings. Looking at the matrix properties (figure 5) the pore throat size, which is arguably the most important controlling property controlling the caprock barrier function, is ranked as medium-low impact, but when capillary entry pressure is considered (figure 7) it is ranked as a medium impact. As these two are linked this reveals a flaw within the elicitation process. This may be as a result of a forcing an answer that is based on very distinct semi-quantitative scenario uncertainty criteria (table 1) or that the expertise range amongst the "experts" was incomplete.

There was a lot of data to process and looking at linked or similar leakage scenarios contained within a wide ranging study is always likely to result in minor discrepancies in their results. These discrepancies although an interesting reflection on the "experts", generally only vary between adjacent impact ratings. The aim of the study was to identify, assess and rank potential leakage scenarios to support the assessment and decision making for early data collection, field operation and monitoring strategies and as such identifying the highest impact ratings is the key to achieving this aim.

It is also important to highlight that expert elicitation is no guarantee to ensure that you cover all eventualities and obtain all the input data required. If fact during the review process the reviewers highlighted two leakage scenarios that were missing; unknown wells and multiple wellbore failures, both of which are important considerations in caprock integrity. As more experts and indeed non-experts are involved it is likely each would have a leakage scenario to add to the list. This reinforces the important point that expert elicitation and impact analysis should be considered a good starting point when there is little data available. However it is an iterative process, growing and improving as the knowledge develops.

A number of interesting relationships are revealed when the data from the elicitation is considered:

6.1. Correlation between the severity and immediacy of CO_2 leakage

The probability and impact matrix for all the leakage scenarios combined reveals a distinct linear correlation between the severity of the potential CO_2 leakage and the immediacy of the potential CO_2 leakage, as the time frame of the leakage decreases, the severity of the leakage increases, Figure 11

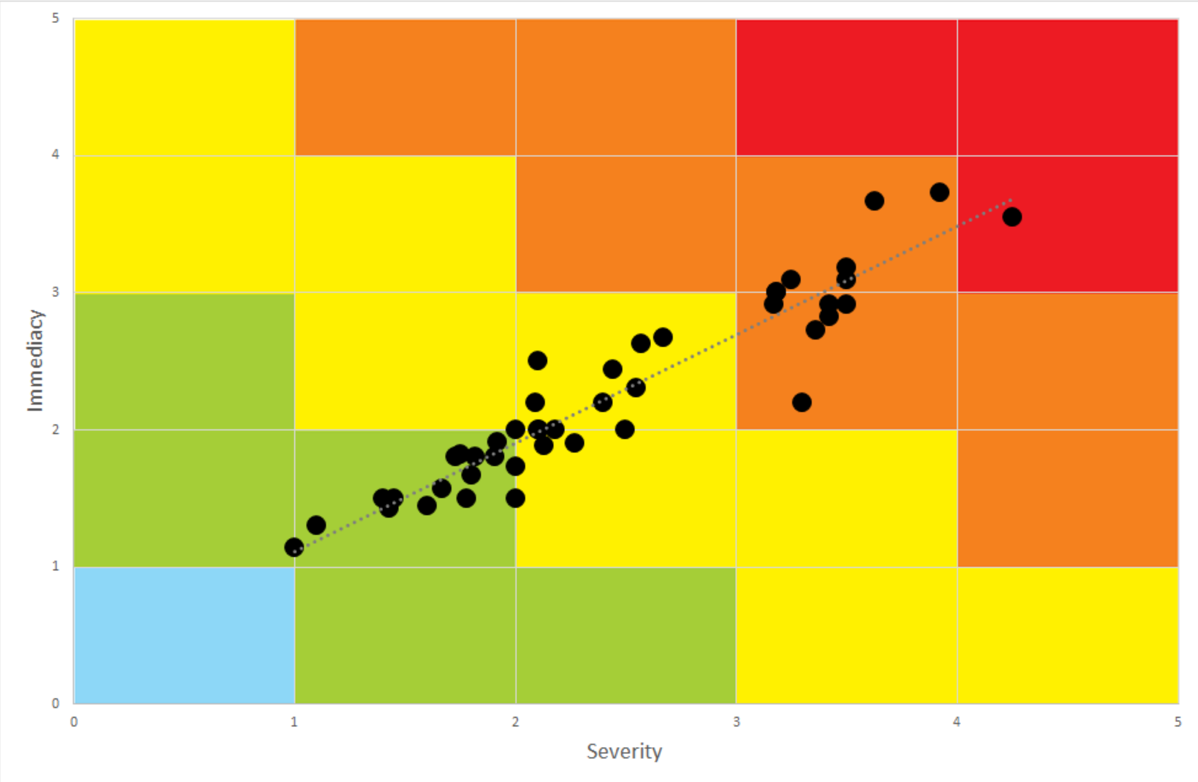

Figure 11 Severity versus immediacy for all the leakage scenarios

This could be because "experts" are relatively conservative, and more likely to give similar values for immediacy and severity, and not a high number for severity and a low number for immediacy or vice versa. It could also be related to a lack of focus or engagement during the elicitation process where the easy option was taken to put middle values for everything. Steps were taken within the design and implication of the elicitation to ensure an engaged participant who at least acquiesced to the process and the fact that not all values were middle range indicate that this is unlikely to be the reason for the linear correlation between severity and immediacy. Elicitation process limitations aside this trend could indicate the important argument that the most significant challenge to storage integrity is during the initial time stages of the storage process, i.e. during injection. It is difficult to identify which of these processes has the dominant control, but the argument that the most significant challenge to the storage integrity of the Heletz injection site is during the initial stages of the storage process (injection) is important and should not be discounted.

6.2. Influence of impact rating on the relationship between severity and immediacy

Looking in more detail at the severity and immediacy of each of the leakage scenarios and in particular looking at the difference between the two, Figure 12, it can be seen that for the lower impact rated leakage scenarios the average severity and immediacy are similar to each other, in that a low severity (scale of the leak) corresponds to a low immediacy (longer timescale of the leak happening), indicating that if the severity of the leakage is low the leakage will happen over a longer timeframe. For the higher impact rating leakage scenarios the difference between the severity (scale of the leak) and the immediacy (timescale of the leak), is generally greater indicating a greater discrepancy between severity and timescale. Overall if the severity of the leakage is high then the timescale will be shorter, reinforcing the previous supposition that the most significant challenge to storage integrity is during the initial time stages of the storage process, during injection.

This data also reassures that the participants did not always give the same values for severity and immediacy and as suggested in section 6.1, but put critical thought into their questionnaire answers.

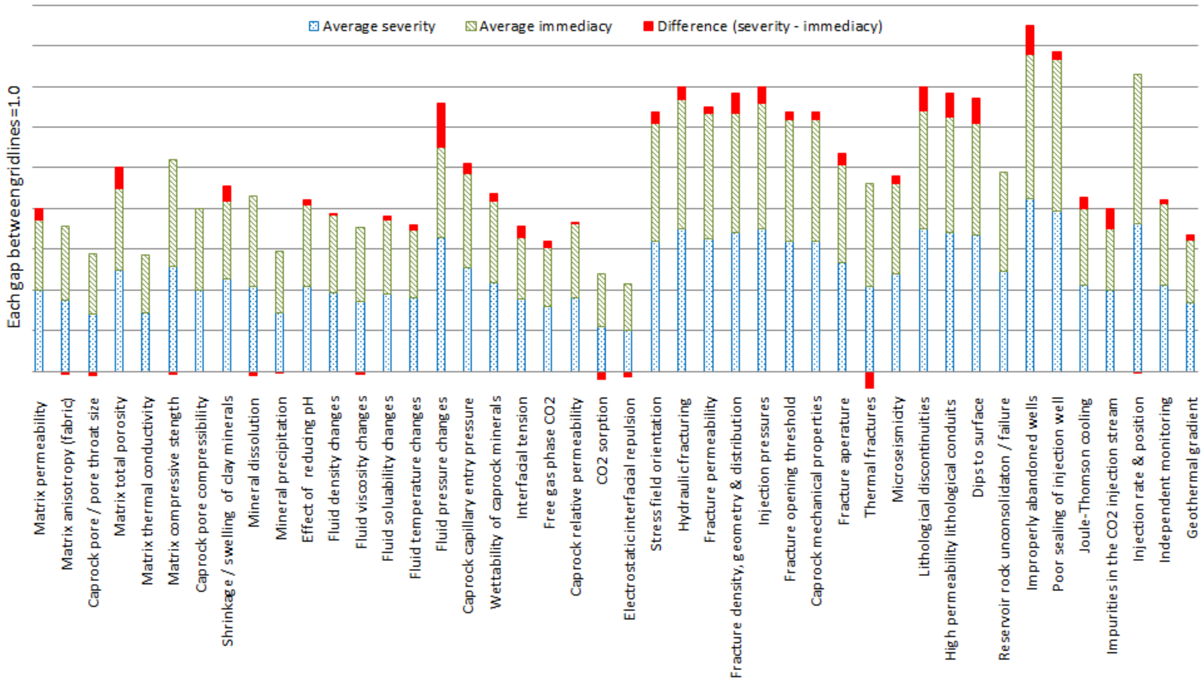

Figure 12 relationship between severity and immediacy

6.3. Uncertainty within the "expert" assessed leakage scenarios

The uncertainty within the "expert's" impact rating of severity and immediacy for each leakage scenario was calculated using the standard deviation of the average severity and immediacy values. Figure 13 presents the uncertainty data for each leakage scenario within the context of the probability and impact matrix. Each scenario is plotted using its arithmetic average severity and immediacy and the error bars on the data point reflects the relative size of the uncertainty using the standard deviation within the severity and immediacy values.

Comparison of the uncertainty associated with the severity and immediacy results imply that in general for the lower to medium impact rating scenarios (caprock matrix properties, mineralogy and the fluids – injection, formation & migrating) there is a smaller degree of uncertainty between the "experts" severity and immediacy estimates.

For the medium to higher impact rating scenarios (the stress / fracturing, well environment and the geological architecture) there is a notable increase in uncertainty between the "expert's" severity and immediacy estimates.

Interestingly for the highest risked scenarios of poor sealing of injection wells and improperly abandoned wells the uncertainty between the "expert's" decreases, indicating a universal agreement that these are the most significant leakage scenarios in ensuring storage security.

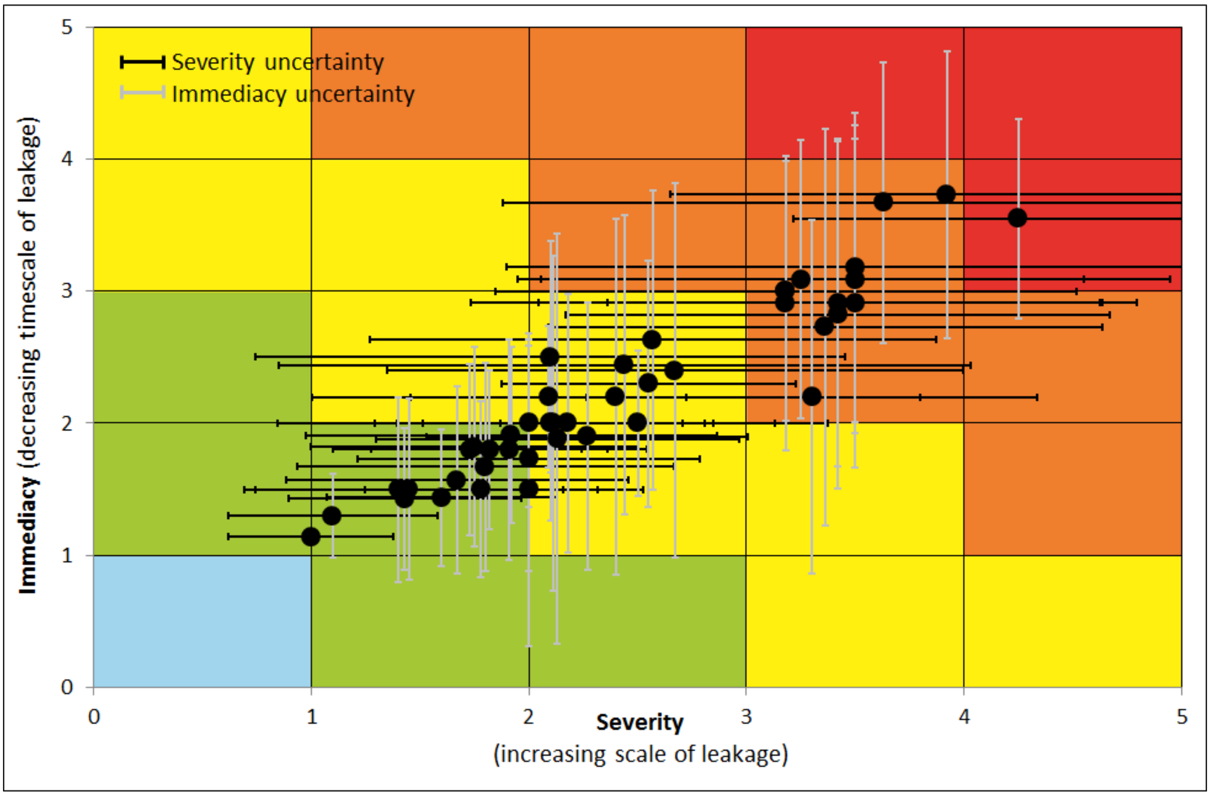

Figure 13 Uncertainty associated with the risk matrix data

6.4. Influence of expert level on elicited impact rating.

Work by Sjobeg and Drottz-Sjoberg (1993) revealed that experts in the nuclear waste field see its risks as much less that the public does, they are more positive towards nuclear power. This may indicate that the more expert a practitioner, the more likely they are to de-risk their area of expertise. To test whether the Heletz "experts" will assign a lower impact rating ("risk") to their area of expertise, an expert level was requested in the questionnaire alongside the severity and immediacy values for each leakage scenario assessed. The first point to note is that of all 12 questionnaires received, only 1 "expert" completed all the expert level boxes, for all other questionnaires the exert level data was extremely incomplete with over five not filling in any expert level values at all. Experts are clearly very shy about declaring their level of expertise, even when assessing their personal expert level against the clearly defined expert descriptions seen in table 2. Figure 14 presents the available expert data for a low impact rated leakage scenario (pore throat size), a medium impact rated leakage scenario (microseismicity) and a high impact rated leakage scenario (poor sealing of injection well. The results do not show any distinct correlations between expert level and impact rating. Due to a lack of data it is not possible to make any meaningful observations on whether expert level influences perception of impact rating.

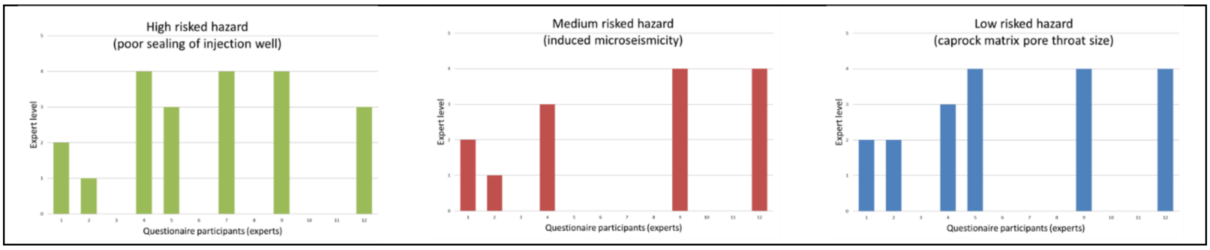

Figure 14 Expert levels for a low, medium and high impact factor rated leakage scenario.

7. Using the expert elicitation results for decision making for early data collection, field operation and monitoring strategies.

The ranked elicitation responses can be used to provide recommendations based upon the fact that data collection and monitoring should be of highest priority and quality in the areas identified by the "experts" as having the highest leakage scenario impact rating. Table 4 presents the Heletz recommendations based on the results from the expert elicitation.

Table 4 Recommendations for early data collection, field operation and monitoring strategies from the elicitation results.

Rank	Leakage scenario	Data collection, operation and monitoring strategies
1	Check for improperly abandoned wells	Pressure test and survey all abandoned wells in the storage area, seismic survey may reveal previously unknown wells.
2	Poor sealing of the injection well	Ensure best practise to minimise risk of poor sealing, test well cement is fit for purpose.
3	Injection rate and position	Undertake modelling sensitivities studies with high quality geology and field input. Plan injection rate and positions carefully to ensure the injection is undertaken as far away from faults as possible and injection rates do not cause significant increases in formation pressure, well, far field and surface pressure monitoring systems in place.
4	Hydraulic fracturing	Determine fracture opening thresholds from pressure tests, lab tests, analogue studies and reservoir modelling. Maintain injection pressures below the fracture opening thresholds.
5	Injection pressures	Undertake modelling sensitivities studies with high quality geology and field input. Maintain injection pressures within capillary entry pressure and fracture opening thresholds.
6	Fracture permeability	Pressure tests along fractures that intersect existing wells, lab tests on analogue or well core. Undertake modelling sensitivities studies with high quality input data.
7	Caprock mechanical properties	Mechanical testing of downhole and representative caprock core with data input into modelling sensitivities studies.
8	Fracture opening thresholds	Pressure tests along fractures that intersect existing wells combined with modelling sensitivities studies with high quality input data.
9	Lithological discontinuities in the caprock	Geological reservoir modelling (and analogue studies) of the interlayered caprock system from seismic and well to well correlation to assess caprock continuity.
10	Fracture density, geometry and distribution	Detailed fracture mapping of caprock from seismic, downhole and analogues. Undertake modelling sensitivities studies with high quality geology and field input.
11	High permeability lithological conduits in the caprock	Geological model (and analogue studies) of the interlayered caprock system from seismic and well to well correlation to identify any high permeability lithology within the caprock.
12	Stress field orientation	Detailed mapping of the downhole stress field
13	Caprock and storage reservoir dipping to surface	Geological model of the whole storage system from seismic and well to well correlation to ensure caprock and reservoir formation does not dip to surface.
14	Fluid pressure changes	Ensure monitoring of near and far field fluid pressures

8. Applicability of the results to other CO_2 storage projects

The results obtained during the "expert" elicitation to identify, assess and rank the potential leakage scenarios at the Heletz pilot CO_2 injection site were compared with the results from more conventional site-specific risk studies from existing CO_2 injection projects, where:

- Deel et al., (2007) concluded from the risk assessment for the Canadian Weyburn field that the greatest risk of leakage was along the wellbore and abandoned wells.
- Oldenburg et al., (2008 and 2011) concluded that for the Algerian In-Salah field the most significant risk of leakage is from the integrity of legacy wells especially if intersecting natural fractures.
- Watson, (2014) concluded from the risk assessment study undertaken for the Australian Otway project that the most likely leakage risks were fault leakage and well leakage from the Naylor-1 Well.
- Jewel and Senior, (2012) concluded that for North Sea CO_2 storage projects, abandoned wells present the most probable source of leakage, followed by loss of well control on active wells with caprock leakage rates low and fault leakage rates uncertain and requiring further work.

As the existing and proposed injection sites are all pre-selected on the basis that their geology is suitable for CO_2 storage, a correlation between the Heletz expert elicitation results and the site specific risk assessment studies from other CO_2 injection sites is not unexpected. However it serves to highlight the important point of any expert elicitation (or indeed conventional risk assessment) study that the experts may be biased by common misconceptions within the CO_2 literature, due to the very nature that they are immersed in this literature.

The findings continue to reinforce the widely held findings that well integrity (abandoned and active), injection pressure and fracture thresholds and geological heterogeneities are the most likely to influence the caprock integrity within a CO_2 storage site.

9. Conclusions

Expert elicitation is widely used where expert knowledge, experience and insight are crucial if the input data and analysis is poorly understood, complex and there is limited 'hard' input data. It has been successfully used within in the fields of nuclear waste, climate change and environmental assessment. An expert elicitation was undertaken to explore the leakage uncertainties at the EU FP7 MUSTANG project Heletz pilot CO_2 injection site by synthesising the reasoned and subjective judgments of experts, because there was insufficient Heletz field data available. The aim of the elicitation was to identify, assess and rank the potential leakage scenarios, to support the assessment and decision making for early data collection, field operation and monitoring strategies.

Simple mathematical aggregation methods of arithmetic average giving equal weight to all experts was used for the data analysis. To rank the leakage scenarios the average expert's data for severity and immediacy were plotted in a probability and impact matrix. This assigns an impact rating from low, medium low, medium, high to very high. The ranked elicitation responses show that there was one extreme impact rating leakage scenario identified by the "experts", that of improperly abandoned wells and thirteen high impact leakage scenarios that the "experts" believe pose the highest likelihood of CO_2 leakage. Leading to the recommendation that these fourteen leakage scenarios merit the highest effort of data collection, sensitivity analysis effort and enhanced monitoring and mitigation strategies.

There was agreement when the Heletz elicitation results were compared with the results from more conventional site-specific risk studies from existing CO_2 injection projects. However it serves to highlight the important point that for any expert elicitation (or indeed conventional risk assessment) study the experts may be biased by common misconceptions within the CO_2 literature, due to the very nature that they are immersed in this literature. The results can be viewed as supporting the widely held findings that well integrity (abandoned and active), injection pressure and fracture thresholds and geological heterogeneities are the most likely to influence the caprock integrity within a CO_2 storage site.

The processes and lessons learned from the Heletz leakage expert elicitation were:

- A comprehensive inventory of forty four sources of potential CO_2 leakage through the caprock (scenarios) was generated for the Heletz site. This became the basis for the expert elicitation. It is pertinent to include all scenarios even those that seem immaterial and there is no guarantee all scenarios will be captured at this stage. Indeed during review two additional leakage scenarios were suggested.
- Twelve experts were selected from within the MUSTANG project group, encompassing a balance of expertise in field characterisation, processes, modelling and assessment. When considering expert bias these experts could be viewed as pro-CO_2 storage, however these biases can be minimised with a well-designed elicitation procedure.

- Semi-quantitative scenario uncertainty criteria of severity (how extensive the CO_2 leakage could be) and immediacy (the potential time period of the leakage) were used to assess the leakage scenarios. No qualitative words such as "likely" or "possible" were used to ensure that linguistic nuances did not create additional uncertainty and a five scale point was used to ensure a defined answer could be identified from the choices. If there are more than seven scale points' participants are likely to pick answers at random. Expert level was also requested in the questionnaire again on a semi-quantitative five point scale to identify if expert level adds a bias to the assessments.
- The experts received a copy of the elicitation question and unbalanced key information providing a brief synopsis of each leakage scenario identified including the limited Heletz data that was available at the time of the elicitation. This was to encourage the "experts" to start thinking about their response in advance.
- A questionnaire completed during a dedicated one hour workshop was chosen for the elicitation process this was because personal interviews were not possible and group interaction can be influenced by dominant personalities in the group and the implicit suggestion of the "need to achieve consensus". The questionnaires were anonymous to minimise the possibility of "experts" feeling exposed by their answers.
- The elicitation question was "What is your best guess of the likely severity (extent of the leakage) and immediacy (time frame) potential of CO_2 leakage for each identified leakage scenario?" Considerable time and care along with multiple iterations of format and question wording was undertaken and tested on colleagues before the final format, question and scales were decided upon.
- Managing the questionnaire workshop was the most challenging aspect of the whole elicitation process. An introduction was given to raise awareness of unconscious bias, reminding the participant's that consensus was not the primary objective. They were also asked to think of the reasoning to support their judgments and consider how the results could be different during the questionnaire answering process to help improve the quality of their assessments. The questions were asked one scenario at a time; the "experts" gave a severity, immediacy and expert level answer for the scenario under scrutiny, then all participants moved onto the next scenario, in addition engagement and refreshments were freely available, all designed to minimise the chances of the "experts" getting bored or providing lax or random middle ground answers, ensure engagement to maximise the potential for a serious and considered response and increase the validity of the results. The elicitation process also required a good deal of encouragement requiring frequent persuasion and reassurance.

Prudent expert elicitation can provide useful insight and guidance and make a valuable contribution to decision making, however if done improperly it can equally lead to invalid or misleading results, wrong decisions and contribute to discrediting the entire expert elicitation approach.

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Supplementary information

1. Questionnaire

Expert Elicitation Questionaire	Severity of leakage scale	immediacy of leakage scale	Level of expertise on risk factor	
	1 - CO_2 intrusion into the mm of the primary caprock	1 - Leakage happens after 10000 years	1 - Novice (no knowledge at all of the leakage hazard)	
	2 - CO_2 intrusion above primary caprock layer	2 - Leakage happens after 1000 years	2 - Limited knowledge (some awareness and knowledge of the leakage hazard)	
	3 - CO_2 intrusion above secondary caprock layers	3 - Leakage happens after 100 years	3 - Competent (working knowledge of the leakage hazard)	
	4 - CO_2 intrusion above tertiary caprock layer	4 - Leakage happens after 10 years	4 - Knowledgeable (research activity and peer reviewed publications of the leakage hazard)	
	5 - CO_2 intrusion into top overburden / to surface	5 - Leakage happens during the injection period	5 - Expert (recognised expert through research, peer reviewed papers and keynote speaker in this leakage hazard)	

Leakage Scenario	Best estimate severity	Best estimate immediacy	Your expert level on hazard	Assessor comments
Matrix permeability	*insert value between 1 and 5*	*insert value between 1 and 5*	*insert value between 1 and 5*	*add any relevant comments*
Matrix anisotropy	*insert value between 1 and 5*	*insert value between 1 and 5*	*insert value between 1 and 5*	*add any relevant comments*
Matrix pore throat size	*insert value between 1 and 5*	*insert value between 1 and 5*	*insert value between 1 and 5*	*add any relevant comments*
Matrix porosity	*insert value between 1 and 5*	*insert value between 1 and 5*	*insert value between 1 and 5*	*add any relevant comments*
Thermal conductivity	*insert value between 1 and 5*	*insert value between 1 and 5*	*insert value between 1 and 5*	*add any relevant comments*
and so on.....	*insert value between 1 and 5*	*insert value between 1 and 5*	*insert value between 1 and 5*	*add any relevant comments*

2. Inventory of leakage scenarios

This is the unbalanced key information given to the "experts" prior to the elicitation session, providing a brief synopsis of each leakage scenario identified including the limited Heletz data that was available at the time of the elicitation.

2.1. Caprock matrix properties

Caprock matrix permeability, pore size and porosity: Small pore throat sizes generate high capillary pressures which effectively inhibit CO_2 flow through the caprock pore structure, (Angeli et al. 2009). Heletz porosity measured on core from Heletz well 18 give values of 7.78%, 10.82%, 8.36%, 8.81% and 5.75%. The permeability measurement from a single caprock core from Heletz well 18 gave a permeability of $4x10^{-15}m^2$, which is extremely high. This can be explained by the fact the caprock cored was a very silty mudstone and that the particular sample measured had a 3cm silt lens within the mudstone and is not considered representative of the caprock as a whole.

Caprock matrix anisotropy and mechanical properties: Matrix anisotropy mainly depends on preferred orientations of rock-forming minerals, single crystal properties, the fracture and pore distribution, and pressure-temperature conditions, (Hornby et al., 1994; Sayers, 1994 & 2005 and Lonardelli et al., 2007). Preferred orientation or texture is caused by slow sedimentation of plate-shaped clay minerals that favours orientation of platelets parallel to the sediment surface. This pattern is modified during compaction and diagenesis (Swan et al., 1989). Anisotropy and mechanical strength control Kv/Kh and fracture propagation and direction so play an important part in understanding long term CO_2 storage integrity.

Pore compressibility: Pore compressibility is the fractional change in pore volume of the rock. As fluid pressures change, the pore network will respond depending on the caprock pore compressibility, (Reike, 1974).

Thermal conductivity: Heat transfer and the associated thermal induced stresses have the potential to open migration pathways or alter existing pathways, (Robertson, 1979 and Weaver, 1979).

2.2. Caprock mineral alteration

For the Heletz caprock samples the primary mineral is K-feldspar (ranging between 30-50%) followed by plagioclase feldspar (10-15%) then kaolinite, illite and muscovite at 5-10% each, with H-2 having slightly more kaolinite that H-18. The minor minerals are then quartz, calcite, pyrite, chlorite and ankerite with traces of siderite and anhydrite, **Error! Reference source not found.** (Edlmann et al. 2015).

Table 5 Heletz well H-18 caprock mineralogy results (values are mineral weight %)

PH alteration and buffering: Depressed pH enhances the dissolution of minerals, as protons substitute for metal cations in the mineral structure, increasing porosity and creating potential flow pathways.

***Shrinkage / swelling of clay minerals*:** Kaolinite becomes unstable at higher temperature and pressure and will react with cations to form illite: kaolinite + cation (K^+) = illite + quartz + water (Velde, 1995). Experimental results suggest that exposure to CO_2 can lead to shrinkage of the montmorillonite or smectite clay minerals (loss of interlayer water), that iron (Fe) may be released from smectites and for Na-smectite expansion of up to 15% was observed upon CO_2 uptake; Amann et al. (2011) and Harrington et al (1999). Work by Loring et al. (2013) has shown that CO_2 can migrate into the montmorillonite clay interlayer and can contribute to expansion, so the extent of montmorillonite swelling depends on both the water and CO_2 concentrations, depending on the amount of water dissolved in the $scCO_2$ at a given pressure and temperature. Smectite is also subject to early diagenetic alteration along with kaolinite and dissolves at temperatures around 65-75oC and often weather to illite: smectite + K^+ = illite + silica (via mixed layer minerals), Bjorlykke et al. (1995). The mineralogy information for Heletz is limited to one well (H-18) and may not be representative of the whole caprock, especially with regard to swelling clays.

Mineral dissolution: Depressed pH enhances the dissolution of minerals, as protons substitute for metal cations in the mineral structure, increasing porosity and opening potential flow pathways.

Mineral precipitation: Aquifers containing 'basic' silicate minerals with a high proportion of Mg and Ca, such as olivine, serpentine, pyroxenes and plagioclase have the greatest potential to fix CO_2 as carbonate minerals because they have a high molar proportion of divalent cations and they react rapidly to form carbonate minerals, also releasing SiO_2, (Xu et al., 2005).

2.3. Fluids – injection, formation, migrating and free phase

Satrinsky (1974) indicates a maximum temperature of 50-60^{o}C at 1500-1800m for the Heletz reservoir and internal MUSTANG reports from the Heletz drilling site provided salinity data from well H-38 defined by DST of 35,000 – 40,000ppm at 1050m depth and 22,113ppm Cl at 1555m.

***Fluid density*:** CO_2 increases in density with increasing depth and it becomes a supercritical fluid above pressures of 7.38MPa and temperatures of 31.1^{o}C. CO_2 is more buoyant than formation water so will rise in a plume, although perhaps slower in its supercritical state, (Muller, 2011).

Fluid viscosity: Viscosity of CO_2 is a very important fluid parameter influencing buoyancy of CO_2 in the reservoir and the viscous drag of the fluid through the pores. It is pressure and temperature dependant which vary within the reservoir so CO_2 viscosity will change during injection and storage, (Fenghour et al., 1998 and Ciotta et al., 2010).

Fluid Solubility: More water dissolves into $scCO_2$ than it does into gaseous phase CO_2. The solubility of water into CO_2 is an order of magnitude less than the solubility of CO_2 into water, (Enick and Klara, 1990).

***Fluid temperature*:** The injection of CO_2 induces temperature alterations leading to thermal stresses which depending on the rock mass characteristics at a local scale can be of the order of magnitude similar to the tectonic stresses, (McDermott et al., 2006) and may lead to fracturing of the caprock.

Fluid pressure: Laboratory experiments have shown that increasing pore fluid pressure (P_f) in low permeability caprocks leads to a lowered effective stress $\sigma' = (\sigma - P_f)$, this reduction in effective stress can result in a reduction in the caprock strength which can induce brittle failure, (Handin et al.,1963; Blanpied et al.,1992 and Nygard et al., 2006). Hydro fracturing is thought to occur when the pore fluid pressure below the top seal equals or exceeds the minimum horizontal stress plus the tensile strength of the caprock, (Watts, 1987). Effective normal stresses ($\sigma n - P_f$) press fault blocks together and resist any sliding motion (shear) along the fault therefore higher pore pressures decrease the resistance to sliding and can instigate shear fracturing. Higher pore pressures decrease the normal stress across the fault lowering the frictional resistance to sliding and can lead to shearing.

Capillary entry pressures: CO_2 injection and buoyant CO_2 flow causes an increase in the formation pressure across the caprock / reservoir formation boundary. The capillary entry or threshold pressure P_c of a caprock depends on the capillary forces in the rock matrix, (Muller, 2011). Busch, (2010) has shown that with an overpressure of 2MPa above the capillary entry pressure, CO_2 breakthrough of the caprock occurs after hundreds to thousands of years for medium to low permeability caprocks with a realistic thickness of 100m, in line with findings by Deming, (1994).

Wettability: Experimental work undertaken by Chiquet, (2007) showed that $scCO_2$ exhibits a stronger wetting behaviour than gaseous CO_2. The wettability contact angle (θ) for gas CO_2 on quartz and muscovite were both around 170^o – 150^o, whereas for $scCO_2$, θ was 140^o for quartz and 120^o for muscovite. Caprock mica and shales are known to be water wet in the presence of hydrocarbons - in the presence of CO_2 there is a transition from water wet at low pressure towards an intermediate wettability at high pressure (above 10MPa) which is more pronounced in the case of mica than for quartz. In terms of reservoir integrity, the changing wetting behaviour under pressure of the CO_2 could lead to an earlier capillary breakthrough through the caprock.

Interfacial tension: Carbon dioxide is highly compressible therefore pressure and temperature have a pronounced effect on the interfacial tension in the CO_2/ water system. Existing experimental data reviewed by Hildenbrand, (2004) shows that the water /CO_2 IFT values fall in the range 20-35mNm^{-1} for pressures in the range 6-20MPa and temperatures below 71^{o}C (equivalent storage depths 600-2000) - these are about half that of water/hydrocarbons - therefore the sealing capacity of caprock with respect to CO_2 is lower than it would be to hydrocarbons.

Free gas phase CO_2: Free-phase CO_2 is CO_2 that remains in the gas (or supercritical fluid) phase and is not immobilized by residual gas trapping.

Relative permeability: In general, low relative permeabilities are observed for $scCO_2$ and the relative permeability of brine is higher, especially during subsequent draining and imbibition cycles where brine effectively traps CO_2 and limits its flow (Bennion and Bachu 2006 and Muller 2011).

CO_2 sorption: Sorption measurements by Amann, (2011) indicate a max sorption capacity of coal of between 0.25 and 0.63 mmol/g., even thin coal / organic layers may be an important sink for CO_2.

Electrostatic interfacial repulsion: The decrease in brine pH that follows CO_2 dissolution (at pressures over 8MPa) cancels or strongly decreases the surface negative charges carried by the mineral / brine and brine/CO_2 interfaces. This depresses the electrostatic interfacial repulsion between clay layers, producing a disjoining pressure which is the pressure difference between the water in the clay structure and the water in the formation, (Goncalves at al., 2010) and can influence shale swelling pressures and porosity.

2.4. Stress state / fracture network

The Heletz field is known to be bounded on one side by a large normal fault, Figure 1.

Stress field orientation: Increased formation pressures due to CO_2 injection and fluid pressure increase can potentially open fractures and cause slip on faults that exist in a reservoir. Knowledge of the relative orientation of the in situ stress tensor and pre-existing faults is an essential prerequisite for analysing the slip tendency of faults, (Streit and Hillis, 2004).

Hydraulic fracturing: Hydraulic fractures are formed when the pore pressure exceeds the sum of the minimum total stress and tensile strength of the sediment, (Watts, 1987 and Nygard et al., 2006).

Fracture permeability: Changes in fracture permeability during loading are functions of the fracture aperture, roughness and asperity strength in relation to the normal and shear stresses applied across and along the fracture, (Nygard et al, 2006 and McDermott & Kolditz, 2006). Fracture surfaces are multi-faceted and can become either barriers or conduits to flow. To assess the transmissibility of a fracture three methods can provide an indication of the sealing capability of the fracture surface: Clay smear potential, (Bouvier et al., 1989); Shale smear factor, (Lindsay et al., 1993) and Shale gouge ratio, (Yielding et al., 1997). All three methods are based on estimates of the distribution of clay along faults and highlight that a clay rich fracture surface will add its own complexity to the multiphase flow of formation fluids and injected CO_2 across a fracture surface.

Fracture density (network geometry and distribution): Geometric properties of fractures which affect fluid flow include spacing (or frequency) persistence, length, orientation and connectivity, (Nygard et al, 2006).

Injection pressures: CO_2 injected into the storage formation increases formation pressure which leads to an increase in pore pressure. An increase in pore pressure can cause dilation in the adjacent layers, a transient increase in overburden stress, and a deficiency in horizontal stresses which can lead to micro shear fractures in the adjacent layers, especially at the reservoir boundaries. Increasing formation pressures can also lead to a decrease in the effective stresses which can reactivate the existing fractures or faults, induce hydro fracturing and instigate shear fracturing in the overlying caprock, (Ellis et al. 2011).

Fracture opening threshold (ductility / brittleness of the caprock): Fracturing is controlled by the ductility or brittleness of the mudrock and the effective confining stress. Ductile behaviour is characterised by contractive response and gradual deformation to failure, usually producing more diffused deformation. Brittle deformation is characterised by dilative response and sudden failure at a well-defined peak shear strength followed by strain softening down to residual shear strength, possibly accompanied by distinct shear failure surfaces, (Nygard et al., 2006).

Fracture aperture: Ingram and Urai, (1999) looked at fracture aperture in relation to hydrocarbon phase flow through cap rock, they observed a small variation on hydraulic conductivity between the phases; however there is a large decrease in hydraulic conductivity as aperture reduces.

Thermal stress: Even small changes in temperature over a reservoir can lead to thermal fractures forming, McDermott et al. (2006).

Microseismicity: Induced by fluid pressure changes, thermal stresses or earthquakes during injection by the resultant pressure wave that passes through the whole reservoir, (Sminchak et al. 2002).

2.5. Geological architecture

Lithological discontinuities in the caprock, caprock pinch out: The Heletz anticline reservoir sands pinch-out into the caprocks, but with limited seismic information if the caprock thins out or has been eroded in the past this could increase the risk of CO_2 leakage, (Gibson-Poole et al. 2009 and Class, 2009).

High permeability lithological conduits within the caprock: If there are high permeability lenses through the caprock they could act as flow paths through the caprock. The cored caprock from well H-18 are very silty, **Error! Reference source not found.**. For significant flow they would have to be continuous or linked, (Class, 2009).

Figure 15 Heletz H-18 caprocks

Caprock and storage reservoir dips to surface - vulnerable strata: The caprock structure and storage reservoir ultimately ends up at the surface, (Gibbson-Poole et al. 2009), with limited seismic information if the caprock thins out or has been eroded in the past this could increase the risk of CO_2 leakage.

Reservoir rock unconsolidation or failure: Reservoir rock loses its cohesion causing collapse of the overlying caprock, (Class, 2009).

2.6. Wellbore environment

Improperly abandoned wells: Leakage could occur through old improperly abandoned wells, (Class, 2009).

Poor sealing of injection well: Casing break, poor cement seal, incorrect cement type, borehole breakout and seal rupture of injection well are all possible sites for CO_2 leakage, (Class, 2009).

Joule-Thomson cooling: Sudden depressurisation of $scCO_2$ will generate solid CO_2 (dry ice) - this can freeze formation fluids leading to expansion of water in fluid filler fractures and / or in effect mitigate release of CO_2 as the dry ice contributes to strong flow interference and low effective permeabilities. The resultant thermo-mechanical stresses during freezing could contribute to open micro-annuli at cement/geology or cement/casing interface, or contribute to cement cracking, (Le Guen et al., 2012).

Impurities in the CO_2 injection stream: The presence of impurities in the CO_2 stream may have an effect on both flow behaviour due to changes in phase behaviour with respect to pure CO_2 and geochemical reactions in the vicinity of the injection well.

Injection pressure, rate and position: Increased fluid pressures during injection and travel through the reservoir including buoyant forces, (Class, 2009).

Independent monitoring: Third party monitoring of any leakage by an independent third party could contribute to leakage paths depending on how invasive and well regulated the monitoring procedures are.

Geothermal gradient: The geothermal gradient, which varies from 0.02°C^{-m} to 0.04°C^{-m}, controls changes in the density of CO_2, and highlights an important balance between pressure, depth and CO_2 properties:

- Cold basins (geothermal gradients 20 - 23^{o}C/km) will need a much higher burial depth to ensure the CO_2 is stored in a supercritical state.
- However with cold basins, once the fluid is in its supercritical state it will have a higher density so any buoyancy effects are lower and up-dip migration of the CO_2 plume will be slower, because CO_2 density increases with pressure and decreases with temperature.
- This complex interplay between temperature and pressure and its effect on the density and viscosity of CO_2 mean that the effect of a deeper burial (higher pressure) below 2km is offset by the increased geothermal gradient (temperature).